

# New signals in dark matter detectors

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**Abstract.** We investigate the scattering of solar neutrinos on electrons and nuclei in dark matter direct detection experiments. The rates of these processes are small in the Standard Model, but can be enhanced by several orders of magnitude if the neutrino sector is slightly non-minimal. This makes even the current generation of dark matter detectors very sensitive to non-standard neutrino physics. Examples discussed here are neutrino magnetic moments and toy models with a simple hidden sector containing a sterile neutrino and a light new gauge boson (“dark photon”). We discuss the expected event spectra and temporal modulation effects, as well as constraints from a variety of astrophysical, cosmological, and laboratory experiments.

## 1. Neutrino interactions in dark matter detectors

It is well known that solar and atmospheric neutrinos constitute an irreducible background to future dark matter searches (see for instance [1]). In particular, neutrinos can scatter on atomic nuclei or electrons, thus mimicking typical dark matter signatures. In this talk, based mostly on ref. [2], we assume that the neutrino sector is slightly non-minimal and show that, in this case, neutrino signals in dark matter detectors can be up to several orders of magnitude stronger than in the Standard Model, enough to make them highly relevant even in the current generation of experiments. (This is also discussed in refs. [3, 4].)

At the basis of our discussion lies the observation that interactions mediated by particles much lighter than the typical momentum transfers in the process become stronger at low energy. Hence, if such interactions exist in the neutrino sector, they may be very significant in dark matter detectors with their low energy thresholds of 10 keV, while dedicated neutrino detectors, whose energy thresholds are at least a few hundred keV would be insensitive to them.

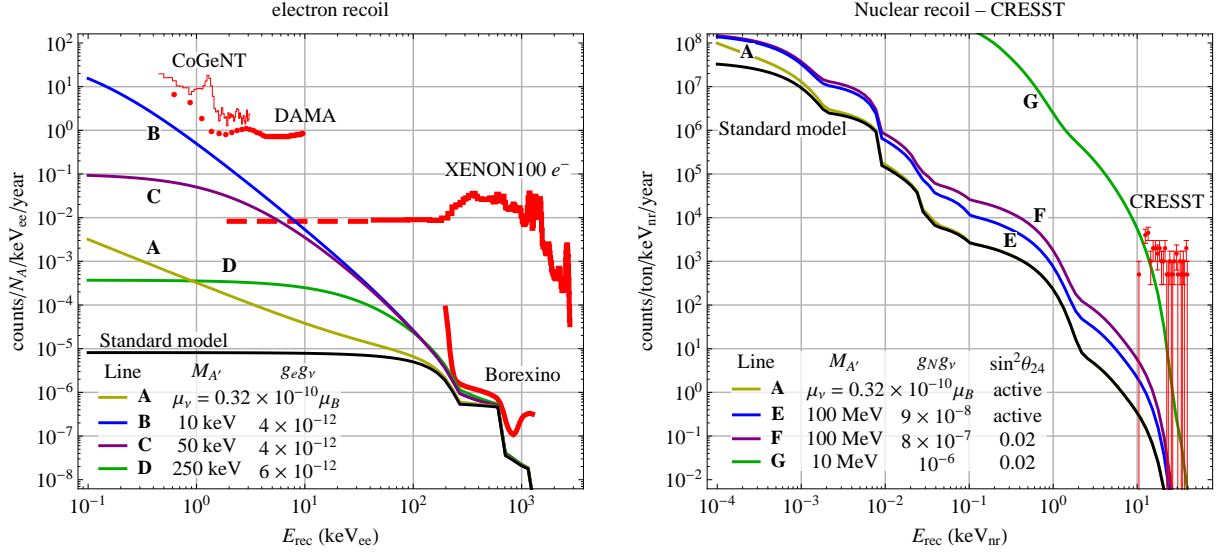
We consider here two examples for light new physics in the neutrino sector: A neutrino magnetic moment (where the light mediator is the photon) and scenarios with a gauged sterile neutrino sector (where the light mediator is a new  $U(1)'$  gauge boson).

### 1.1. Neutrino magnetic moments

Neutrino magnetic moments are described by a Lagrangian operator of the form

$$\mathcal{L}_{\mu\nu} \supset \mu_\nu \bar{\nu} \sigma^{\alpha\beta} \partial_\beta A_\alpha \nu, \quad (1)$$

where  $A_\alpha$  and  $\nu$  denote the photon and neutrino fields, respectively,  $\mu_\nu$  is the neutrino magnetic moment, and as usual,  $\sigma^{\alpha\beta} = \frac{i}{2}[\gamma^\alpha, \gamma^\beta]$ . The Standard Model prediction for  $\mu_\nu$  is negligibly small [5], but in extensions of the Standard Model, it can come close to the current experimental



**Figure 1.** Neutrino–electron scattering rates (left) and neutrino–nucleus scattering rates for germanium (right) in the Standard Model (black) and in various models with extended neutrino sectors (colored lines). The curves labeled (A) illustrate the effect of a neutrino magnetic moment  $\mu_\nu = 0.32 \times 10^{-10} \mu_B$ ; curves (B, C, D) are for a model where neutrino scattering is enhanced by exchange of a new  $U(1)'$  gauge boson with mass  $M_{A'}$  and couplings to neutrinos ( $g_\nu$ ) and electrons ( $g_e$ ) or nucleons ( $g_N$ ) as given in the legend. This is, for instance, realized in scenarios with a sterile neutrino charged under  $U(1)'$ , and coupled to Standard model particles through kinetic mixing of the  $U(1)'$  gauge boson and the photon. Curve (E) shows model with active neutrino–nucleus scattering through a light  $A'$  boson (for instance a  $U(1)_{B-L}$  model), and curves (F) and (G) illustrate a situation in which 2% of solar neutrinos oscillate into a “sterile” state  $\nu_s$ , which is, however, charged under a  $U(1)_B$  gauge group broken at a low scale [3]. We compare the model predictions to observed event rates in various experiments (red curves and data points) [7–11]. Figure taken from ref. [2].

90% CL upper limit  $\mu_\nu < 0.32 \times 10^{-10} \mu_B$  (where  $\mu_B = \sqrt{4\pi\alpha}/2m_e$  is the Bohr magneton, with  $\alpha$  the electromagnetic fine structure constant and  $m_e$  the electron mass). The magnetic moment-induced neutrino–nucleus scattering cross section is [6]

$$\frac{d\sigma_\mu(\nu N \rightarrow \nu N)}{dE_{\text{rec}}} = \mu_\nu^2 \alpha Z^2 F^2(E_{\text{rec}}) \left( \frac{1}{E_{\text{rec}}} - \frac{1}{E_\nu} \right), \quad (2)$$

with the notation  $E_\nu$  for the neutrino energy and  $E_{\text{rec}}$  for the nuclear recoil energy. Note that  $d\sigma_\mu/dE_{\text{rec}}$  is proportional to the square of the nuclear charge  $Z$  because at low  $E_{\text{rec}}$  the scattering is coherent on all protons in the nucleus. At higher  $E_{\text{rec}}$ , loss of coherence is taken into account by the nuclear form factor  $F(E_{\text{rec}})$  [2]. The neutrino–electron scattering cross section is given by eq. (2) with  $Z$  and  $F(E_{\text{rec}})$  set to 1.

The differential neutrino–electron and neutrino–nucleus scattering rates in the magnetic moment scenario are shown as a function of  $E_{\text{rec}}$  in fig. 1 (curves labeled “(A)”). They exhibit the increase with  $1/E_{\text{rec}}$  expected from eq. (2) at low energy, which leads to an enhancement of more than one order of magnitude at 1 keV recoil energy compared to the Standard Model.

### 1.2. Sterile neutrinos and a light $U(1)'$ gauge boson

An even larger enhancement of neutrino scattering rates in dark matter detectors occurs in scenarios featuring, in addition to the massless photon, another relatively light ( $\ll 1$  GeV) gauge boson (“dark photon”). Since couplings of such gauge bosons to Standard Model particles are strongly constrained [2, 12, 13], the most natural scenario of this type is one in which, in addition to the three active neutrinos, a sterile neutrino sector exists which is uncharged under the Standard Model gauge group, but couples to the new  $U(1)'$  gauge force. The sterile sector can communicate with the Standard Model sector through a kinetic mixing term of the form

$$\mathcal{L}_{\text{mix}} = -\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}, \quad (3)$$

where  $F_{\mu\nu}$  and  $F'_{\mu\nu}$  are the electromagnetic and  $U(1)'$  field strength tensors, respectively, and  $\epsilon$  is the small mixing parameter. (An alternative possibility is a  $U(1)'$  gauge boson which couples only to the sterile neutrinos and Standard Model quarks, but not leptons [3, 4].)

The sterile neutrinos can be produced in the Sun through their small mixing with the active species, and they could scatter on nuclei in a terrestrial detector with differential cross section

$$\frac{d\sigma_{A'}(\nu N \rightarrow \nu N)}{dE_{\text{rec}}} = \frac{4\pi Z^2 \alpha \alpha' \epsilon^2 m_N F^2(E_{\text{rec}})}{E_\nu^2 (M_{A'}^2 + 2E_{\text{rec}} m_N)^2} [2E_\nu^2 + E_{\text{rec}}^2 - 2E_{\text{rec}} E_\nu - E_{\text{rec}} m_N], \quad (4)$$

where  $\alpha$  and  $\alpha'$  are the electromagnetic and  $U(1)'$  fine structure constants,  $m_N$  is the nuclear mass,  $M_{A'}$  is the mass of the new gauge boson, and the other quantities are defined as in eq. (2). The expression for neutrino–electron scattering is obtained by the replacements  $Z \rightarrow 1$ ,  $F(E_{\text{rec}}) \rightarrow 1$ , and  $m_N \rightarrow m_e$  in eq. (4).

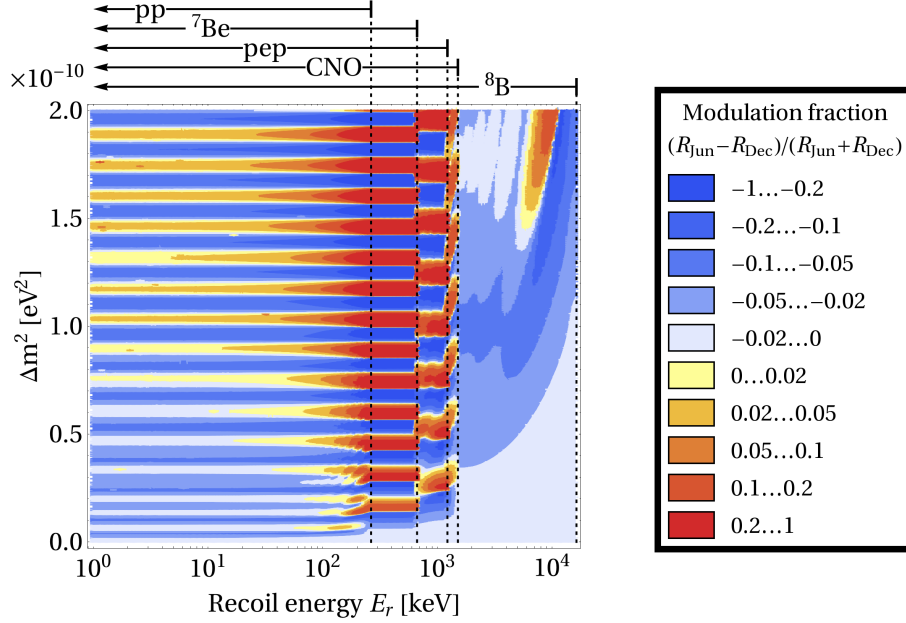
Possible signals of sterile neutrino scattering in dark matter detectors through new  $U(1)'$  gauge bosons are shown in fig. 1, curves (B)–(G). (See plot legend for more details.) We see that these models can easily lead to neutrino signals several orders of magnitude stronger than the Standard Model prediction and thus highly relevant even to current dark matter searches: experiments like Xenon-100 can be extremely sensitive to new physics in the neutrino sector, which significantly enhances their physics case, but can also constitute a problem because often neutrino signals cannot be easily distinguished from genuine dark matter signatures.

This observation raises the question whether sterile neutrinos can explain some of the anomalous signals reported from the DAMA [9], CoGeNT [10], and CRESST [14]. As curve (B) in the left panel of fig. 1 shows, a fraction of the excess events observed in CoGeNT can indeed be accounted for if interpreted in terms of electron recoils and if very conservative assumptions are made on the sensitivity of Xenon-100 to low-energy electron recoils. The CRESST signal could also be partially explained, but note that the energy spectrum of CRESST events cannot be well reproduced, and that models like the one shown in fig. 1 right, curve (D), are constrained by the total event rate in DAMA (see fig. 4 in ref. [2]). The annual modulation signal observed in DAMA will be discussed in the next section.

## 2. Temporal modulation of neutrino signals

Dark matter scattering rates are expected to vary during the year because the Earth’s velocity with respect to the Milky Way’s dark matter halo is larger in summer than in winter [15]. However, also neutrino signals from the Sun are expected to modulate with time.

The simplest source of modulation is the varying Earth–Sun distance caused by the ellipticity of the Earth’s orbit. It leads to a roughly 3% larger expected count rate in winter than in summer, which corresponds to a  $180^\circ$  phase shift compared to the commonly considered modulation signals from dark matter. It is, however, interesting to note, that also dark matter scattering rates can peak in winter in the higher energy parts of the recoil spectrum [15]. Thus, in a

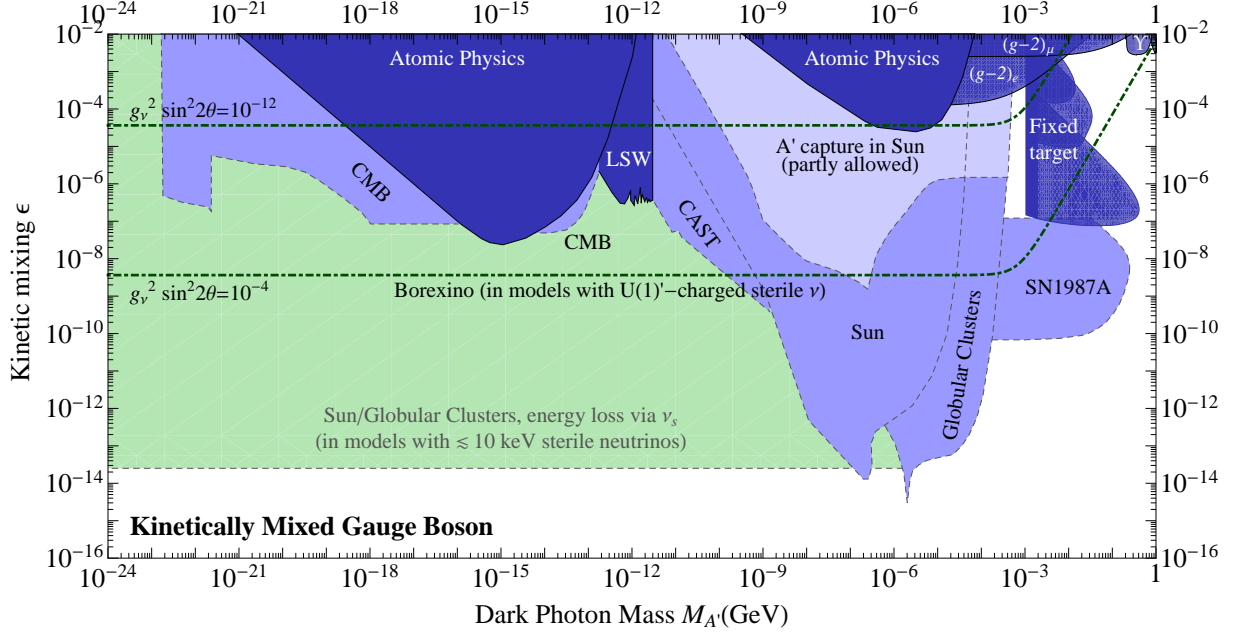


**Figure 2.** Relative annual modulation  $(R_{\text{Jun}} - R_{\text{Dec}})/(R_{\text{Jun}} + R_{\text{Dec}})$  for neutrino–electron scattering events in the  $U(1)'$  model from sec. 1.2 as a function of the recoil energy  $E_{\text{rec}}$  and the mass squared difference between the mostly sterile mass eigenstate and  $\nu_2$ . Here  $R_{\text{Jun}}$  and  $R_{\text{Dec}}$  denote the differential count rate in events per keV at the summer and winter solstices, respectively. We have worked in a 2-flavor framework here. The vertical dashed lines indicate the cutoff energies of the different components of the solar neutrino spectrum. Figure taken from ref. [2].

detector with a high energy threshold ( $\gg 10$  keV), a dark matter modulation signal could be easily mimicked by neutrinos from the Sun.

However, depending on the details of the model, neutrino signals in dark matter detectors can also modulate with a different phase and amplitude. This happens in particular in the model discussed in sec. 1.2, where the fake dark matter signal is due to sterile neutrinos produced through oscillations (see also [3]). The sterile neutrino fraction in the solar neutrino flux can be significantly larger in summer than in winter if the oscillation length is not too different from the Earth–Sun distance, i.e. if the mass splitting  $\Delta m^2$  between the mostly sterile mass eigenstate and the mostly active mass eigenstate  $\nu_2$  which dominates the solar neutrino flux, is of order  $10^{-10}$  eV<sup>2</sup>. We illustrate this in figure 2 by plotting the fractional annual modulation as a function of the recoil energy and of  $\Delta m^2$ . We see that large modulation peaking in summer can occur in large parts of the parameter space, i.e. no extreme fine-tuning is necessary to produce a dark matter-like signal. Note that, even in this case, the modulation phase would differ from the one expected from dark matter by about a month, i.e. a high statistics measurement of annual modulation would still be able to discriminate between dark matter and neutrino signals.

Other sources of temporal modulation of solar neutrino signals are Mikheyev-Smirnov-Wolfenstein type matter effects [16, 17] in the Earth (this typically requires more than one sterile neutrino), sterile neutrino absorption in the Earth, and angle-dependent detection efficiencies (see [2] for details on these modulation mechanisms).



**Figure 3.** Constraints on the mass  $M_{A'}$  and the kinetic mixing parameter  $\epsilon$  (see eq. (3)) of a “dark photon”. Most limits are taken from ref. [13]. See text, as well as ref. [2] and references therein for further details. Figure taken from ref. [2].

### 3. Constraints on dark photons and sterile neutrinos

In sec. 1.2, we have only discussed specific benchmark points for the models under consideration, but it is, of course, important to investigate the full available parameter space. Indeed, a plethora of constraints exist on light gauge bosons (dark photons) and on hidden sector particles coupled to them. Here, we discuss constraints for the specific case of a dark photon coupled to the Standard Model through a kinetic mixing term of the form (3). These constraints are summarized in fig. 3. (For constraints on other types of  $U(1)'$  gauge bosons, see ref. [2] and references therein.)

At large dark photon mass  $M_{A'}$ , constraints come mainly from particle physics experiments, in particular fixed target (beam dump) experiments, measurements of the anomalous magnetic moment  $g - 2$  of the electron and the muon, and  $\Upsilon$  decays studied at  $B$  factories [18–21]. (Note that a dark photon with parameters just below the region labeled  $(g - 2)_\mu$  could explain the observed discrepancy between the measured muon anomalous magnetic moment and the Standard Model prediction [22].)

For  $M_{A'}$  in the eV–MeV region, very strong limits can be derived from stellar evolution: dark photons would provide a very efficient energy loss mechanism for stars and supernovae [13, 23, 24], significantly shortening their lifetime (for stars) or reducing their energy output (for supernovae). The resulting limits are especially strong if  $M_{A'}$  is similar to the typical thermal energies in the star [23], so that  $\epsilon$  is constrained down to  $10^{-14}$  in this regime. Note, however, that dark photons with stronger couplings (indicated by the light blue region in fig. 3) cannot be ruled out this way because they would not be able to leave the star/supernova due to absorption [23]. Limits could still be obtained from stellar evolution constraints on anomalous heat transport inside the star [25], but for  $M_{A'} \gtrsim 100$  keV, we expect these constraints to disappear as well [2, 25].

For sub-eV dark photon masses, the strongest constraints are obtained from helioscopes like

CAST [23], from “Light Shining through Walls” (LSW) experiments [26], from tests of the Coulomb law in atomic physics [27], and from distortions of the CMB spectrum [28].

In models which contain in addition to the dark photon also one or several light sterile neutrinos (like the scenario discussed in sec. 1.2), additional constraints arise from the fact that the sterile neutrino(s) would act as “minicharged particles” [13, 29]. The strongest limits in this case arise again from stellar cooling (light green region in fig. 3) and from Borexino [2, 8].

#### 4. Summary

To summarize, we have shown that rather minimal extensions of the neutrino sector of the Standard Model can lead to very interesting signals in dark matter direct detection experiments. As examples, we have considered scenarios with neutrino magnetic moments and models with a sterile neutrino sector enjoying a new gauge symmetry broken at a scale  $\ll 1$  GeV. We have shown that very large neutrino–electron and neutrino–nucleus scattering rates, well within the reach of current dark matter detectors, can occur at  $\mathcal{O}(10\text{ keV})$  recoil energy. At the higher energies probed by dedicated neutrino detectors, no anomalous signals would be expected.

On the one hand, neutrino signals in dark matter detectors enhance the physics case of these experiments by allowing them to probe additional types of new physics besides dark matter. However, they can also constitute a problem because, especially for small event samples, they can be easily confused with genuine dark matter signals. For instance, we have shown that neutrino signals can exhibit temporal modulation similar to the one expected from dark matter.

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